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SUSTAINABILITY STRATEGIES AND THEIR INFLUENCE ON THE PRODUCT DEVELOPMENT OF MACHINE TOOLS AND SPECIAL MACHINES

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ABSTRACT

In the context of product development, the goal of developers is to design products based on a variety of stakeholder needs so that they sufficiently satisfy a wide range of required characteristics. The required properties relate to function, safety, manufacturability, cost, usability, etc. In recent years, sustainability has gained importance as an additional and now indispensable guiding principle in product development due to the rapidly growing global environmental, social and economic challenges. The focus of this paper is on sustainability, which takes into account resource consumption, environmental protection and ecology. The same applies to the circular economy as an essential component of sustainability strategies when it comes to product or material cycles, as well as the targeted repair, reuse, modification, waste prevention and upgrading of products, etc. A product category that is rarely in the public eye is machine tools and special machines. In order to consistently consider sustainability and the associated circular economy in the development of these machines, product developers need practice-oriented and methodically validated decision-making means. The paper discusses and systematizes possible sustainability strategies and their implications from different perspectives, such as business models or applicability.

Index Terms – machine tools, special machines, sustainability measures, circular economy, business models

1. INTRODUCTION

In the context of product development, the goal of developers is to conceptualize and design products in such a way that they sufficiently fulfill a wide range of required properties. The required properties relate to function, safety, manufacturability, design, cost, etc., which can be influenced by characteristics [1]. In recent years, sustainability has become increasingly important as an additional guiding principle in product development, in addition to the many required properties that already exist. Sustainability, which takes equal account of resource consumption, environmental protection and ecology, concerns all phases of the product life cycle, from manufacture to recycling. The same applies to the circular economy, as part of sustainability strategies, especially when it comes to product and/or material cycles as well as the targeted repair, reuse, modification and upgrading of products, etc. [2]. Certain eco-design measures [3–5] are already helping to make product development decisions that reconcile economic growth with reduced use of natural resources and environmental protection under socially equitable conditions [2, 6–8]. This is particularly true for consumer goods covered by the Energy-Related Products Directive 2009/125/EC.

A product category of particular importance is machine tools and special machines, which represent the highest turnover part of the machinery sector [9]. In the business-to-business (B2B) sector, machine tools and special machines are traded in relatively small quantities, are subject to a wide range of quality requirements, and generally have a relatively long service life. The long service life is a result of both the quality level and the continuity of maintenance and upgrades. According to [10], approximately 80% of the life cycle costs of machine tools and special machines are incurred in the use phase. The main cost drivers are energy consumption (approx. 20%), the use of auxiliary materials (16%), maintenance (37%) and unplanned repairs (9%) [10]. Emissions and other environmental impacts are not included. In order to consistently consider sustainability and circular economy aspects in the development of machine tools and special machines, product developers need practical and methodologically validated tools to make targeted decisions. This is important because sustainable product development only has a chance in the long term if the economic framework conditions are taken into account in addition to social and ecological concerns and economic efficiency and success are ensured [11].

The circular economy as a "regenerative" system must always be understood as an economic model for sustainable development. Measures for technical impacts as well as approaches for product development must therefore always be discussed in the context of entrepreneurial strategies and business models. Business models of the circular economy are often very product-specific and therefore transferable between product categories only to a limited extent [12]. Therefore, a comprehensive understanding of the development of sustainability strategies for circular business models in machine tools and special machines is essential. This is the only way to identify the key cost drivers. These include environmental costs (reduction of the ecological footprint, etc.), raw material costs (costs of material substitution in response to environmental protection and sustainable development requirements, etc.), energy and auxiliary material costs (reduction or even elimination of environmentally harmful substances, etc.), and maintenance costs (predictive maintenance, optimization of spare parts, application of life cycle management).

The paper discusses and systematizes possible sustainability strategies for the machine tool and special machine industries and their impact from different perspectives, such as business models (purchase, leasing, deposit system, pay-per-use, modified pay-per-use, etc.) or applicability (whole machine, specific assemblies or single part). Aspects such as re-use, modification, upgrading and use in other contexts (2nd market) are also considered. Based on these representations, the resulting significant cost influences are explained. The systematized sustainability strategies, the resulting business models and their cost influences ultimately provide the decisive information for sustainable product development. Finally, the requirements for the development of methods and guidelines that product developers need for the development of machine tools and special machines are presented. This serves as a means to ensure reliable statements or specifications on sustainability with all associated target product properties.

2. STATE OF THE ART

2.1 Sustainability strategies

Tackling the climate crisis together is one of the greatest challenges of our time. In recognition of this, the European Union presented the European Green Deal in 2019 [13], as an action plan to ensure the complete climate neutrality of the European Community by 2050 - in terms of CO2 emissions, through a variety of measures. This is based on the Agenda 2030, in which the global community has set itself goals for the socially, economically and ecologically sustainable development of human society [14]. The Sustainable Development Goal 12 listed there addresses the manufacturing sector in particular, as it occupies a key position [15]. The goals can only be achieved if sustainable technologies and business models are developed in a goal-oriented manner.

In the manufacturing industry, especially in the machine tool and special machine industry, the supply chains are often complex due to the number of cooperation partners and the individual production processes, so that a comprehensive assessment of the sustainability aspects under the given boundary conditions is essential in order to identify the decisive levers of influence and to take targeted measures to improve sustainability performance. This enables companies to minimize environmental impact, increase resource efficiency, assume social responsibility and ensure long-term competitiveness. By taking a holistic view of sustainability dimensions, potential risks in supply chains can also be identified and mitigated to achieve sustainable and resilient value creation. Since 2009, the Fraunhofer Gesellschaft has been operating the Sustainability Network in Germany (16 participating research institutes), which is primarily aimed at finding solutions for larger companies and volume manufacturers. Previous and completed project results can be found at [16]. Important publications in this area are e.g. [17, 18].

There are various approaches to assessing and reporting on sustainability, each of which follows specific objectives and therefore includes relevant aspects. Holistic considerations in companies are often documented by means of sustainability balance sheets and sustainability reports (see also German Sustainability Code (DNK), Global Reporting Initiative (GRI), Directive 2013/34/EU, etc.) and also include social components [19]. More specific technical considerations are carried out in the companies, for example, with regard to greenhouse gas emissions (GHG emissions). Here, ISO 14064 and the GHG Protocol provide a basis for the quantitative assessment of emissions. The GHG Protocol distinguishes between 3 scopes for GHG emissions (direct emissions, indirect emissions from purchased energy, and all other indirect emissions, e.g. through the supply chains). ISO 14064 has similar categories. In the context of CO2 accounting, the term "carbon footprint" is often used. Carbon footprinting is the process of determining the environmental impact of a product, service or business [20]. Detailed analyses are required to determine the relevant data. Life Cycle Assessments (LCA) [21] are often used for these analyses.

To reduce the carbon footprint, it is necessary to improve the energy and resource efficiency of products or processes in the different phases of the product life cycle. Key strategic actions are:

1. the design of products to reduce energy and resource consumption in the different phases of their life cycle, from production through use (also in different products), to maintenance and recycling; and

2. the application of circular economy concepts so that different material cycles can be realized, leading to reduced raw material use, waste prevention, the increased use of secondary raw materials, etc.

These key strategies are accompanied by other related approaches. These include the use of renewable energy, the implementation of energy management systems, the reuse of waste, the optimization of processes and supply chains including sustainable procurement, technological innovation, etc. It's equally important to raise employee awareness of sustainability issues. This will help ensure a culture of sustainability within the company.

Sustainable design of products has been studied in numerous sources [4, 5]. This work is often summarized under the term eco-design. The task of product development is now to define and detail the product characteristics in such a way that the target properties of the products are also sufficiently fulfilled from a sustainability perspective. Products generally comprise a very large number of target properties (see CPM model by Weber [1, 22] and Figure 1). There are properties that must always be fulfilled, e.g. machine safety during use. Depending on the product, there are different priorities for the other properties. In eco-design, especially the sustainability properties in particular are given a high priority. Comprehensive Life Cycle Assessment (LCA) [21] are necessary to implement the sustainability properties in a targeted way and to evaluate their impact. In this context, LCA covers the environmental impacts of products, processes or services along the entire product life cycle "from cradle to grave" [23].

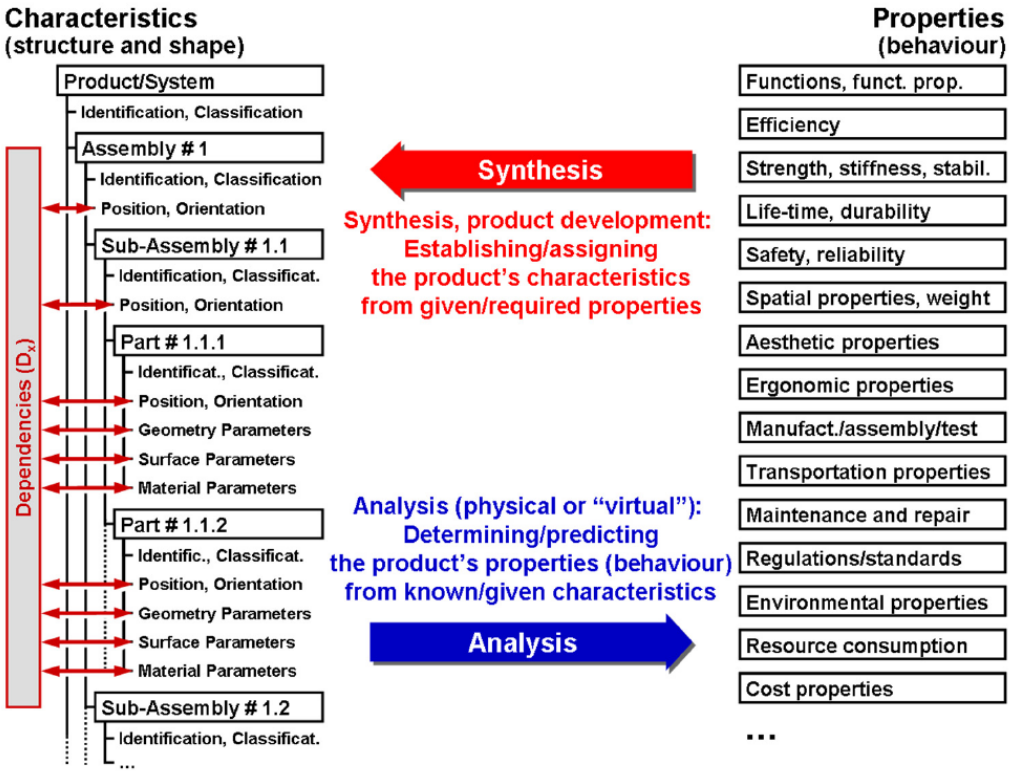

Figure 1. Characteristics and properties, and their two main relationships [1]

From a product development perspective, the circular economy (see also Figure 2) extends eco-design to include new strategic approaches. According to [24], the circular economy is defined as follows "The circular economy is a production and consumption model that involves sharing, leasing, reusing, repairing, refurbishing and recycling existing materials and products for as long as possible. In this way, the life cycle of products is extended".

Figure 2. Concept of circular economy

It is clear that the circular economy approaches are always associated with business model approaches. According to [25], three main strategies can be distinguished in the context of the circular economy:

1. Narrowing Loops: From the point of view of product development, this strategy represents a well-known variant, since resources can be saved and waste reduced by appropriate development measures (eco-design, design for X). From an economic point of view, however, this strategy is difficult to implement with traditional business models.
2. Slowing Loops: The strategy of slowing down the cycles strategy aims to extend the life of a product by allowing it to be used longer through maintenance or upgrades. This strategy is often implemented through extended service business models or the sale of replacement or upgrade components. One possible extension of this strategy is the remanufacturing and resale of products or components [26].
3. Closing Loops: This strategy aims to achieve material cycles through the disassembly of products and the separability of individual materials. This strategy also leads to extended business models, e.g. for the disassembly of products or recycling.

2.2 Machine Tools and Special Machines

Machine tools and special machines are special product groups in the context of sustainability. On the one hand, these machines have a significant impact on the sustainability of the processes they are intended to support. On the other hand, the machines themselves have a carbon footprint. From a development perspective, these machines also have unique characteristics. For example, the number of units of the machines ranges from one, in the case of a specific custom design, to a larger number, in the case of standard machines. The service life of the machines also covers a wide range. For example, some sources speak of service life of a few years for machine tools and special machines (e.g., due to product replacement) [27]. However, especially cross-product machine tools and special machines in particular have much longer service life before they are no longer be used in a technically or economically viable manner. Machine tools and special machines are sold in B2B business, which means that customers usually have specific requirements for the machines. In order for SMEs in particular to be able

to develop and produce the machine tools and special machines economically, a larger number of purchased and standard parts are often used.

3. APPROACH

For the targeted development of sustainable machine tool and special machines, developers and other decision makers in companies need methodical support for strategic and technical decisions. Against this background, this contribution discusses a two-step approach:

1. selection of the target-oriented business model strategy taking into account the relevant influencing factors (see section 3.1) and
2. target-oriented design of the products taking into account the specific business model strategy (see section 3.2).

3.1 Selection of the target-oriented business model strategy

In order to make a targeted decision on the business model strategy, various aspects have to be analyzed and taken into account. Companies have to operate economically in order to survive in the long run. The following explanations are based on the business model strategies according to [25] (see the three main strategies presented in Section 2.1). Strategies always have a medium to long term effect. For machine tools and special machines this means several years according to the service life (see state of the art). Relevant aspects when deciding on the business model strategy are the expected development of customer requirements, technological trends and the regulatory framework conditions. In the context of the machine tool and special machine industry, this results in three main variants:

1. significant changes in customer demand, technology and the regulatory framework (see section 3.1.1) are occurring or are expected to occur
2. in the longer term, no changes in demand, technology or regulatory framework are expected in the longer term (see Section 3.1.2)
3. growing customer requirements or more efficient technologies (see Section 3.2.2).

3.1.1 Business models in the face of significant changes in the framework conditions

If far-reaching changes in demand (e.g. if machines are to manufacture products that will not themselves be on the market for a long time), in technology (e.g. if technological changes in automation or networking are to be expected), and in the regulatory framework conditions (e.g. announced eco-design laws) are to be expected, business model strategies should be selected and appropriate measures taken that contribute to the efficient closing of loops, e.g. through recycling-friendly design. Under the above conditions, the following business models can be considered in the machine tool and special machine industry:

- **Services for the circular economy:**

  By specializing in services that facilitate the efficient closing of loops, companies can play an important role in promoting the circular economy. Through activities such as recycling, reuse and refurbishment of machine tools, special machines and their components, they help reduce waste and maximize resource efficiency. By taking a customer-focused, product lifecycle approach, companies can help their customers implement sustainable solutions and advance their own sustainability goals.

- **Upgrade and repair services:**

  In addition, offering refurbishment/upgrade and repair services not only helps prevent the disposal of obsolete machine tools and special machines, but also helps reduce waste and resource consumption [28]. By refurbishing and upgrading existing equipment, companies can extend its useful service life and maximize its value. In addition to traditional repair services, the integration of innovative technologies can significantly improve the remanufacturing and refurbishment process. Using advanced sensor technologies, data analytics and machine learning, potential areas for improvement can be identified and optimized. By integrating new features and capabilities, companies can increase the value and competitiveness of their machines as customer needs and market demands change. In addition, offering upgrade and repair services can strengthen customer loyalty and create new revenue streams. This creates a win-win situation where customers benefit from extended machine life and improved performance, while companies benefit from service offerings and build long-term customer loyalty.

- **Consulting and training as services:**

  Companies can provide valuable consulting and training services to prepare for anticipated changes in demand, technology and regulations. This includes helping to adapt production processes to meet new requirements, conducting training programs to educate customers' employees on environmental and sustainability practices, and advising on the development of sustainable product concepts. By offering these services, companies can enable their customers to navigate a changing environment, improve their sustainability performance, and drive the adoption of sustainable practices in their operations.

- **Leasing and pay-per-use models:**

  In response to expected changes in demand and technology, companies may increasingly introduce leasing or pay-per-use models [29]. This allows customers to use the machines only as long as they need them, while companies take responsibility for the maintenance, repair, and efficient use of the machines. Such models offer resource savings and optimize operating costs for customers, promote sustainability through more efficient resource allocation, and reduce the overall environmental footprint.

The exemplary business models mentioned above not only focus on closing loops more efficiently, but also aim to maximize resource efficiency and integrate sustainability principles into the machine tool and special machine industry. By adopting these models and adapting to changing needs, technologies and regulations, companies can maintain their competitiveness while actively contributing to sustainability goals. This proactive approach not only benefits the environment, but also strengthens the long-term viability and resilience of the industry as a whole.

3.1.2 Business models with no significant change in framework conditions

If no changes in requirements, technologies or regulatory framework conditions are to be expected even in the longer term, strategies of "slowing" or "narrowing" [25] including repair

options should be discussed, possibly also in conjunction with service models. In this context, the multiple use of products or their components can also be considered [26]. Under the aforementioned conditions, the following business models could be considered in machine tool and special machine industry:

- **Maintenance (Inspection and Repair) services:**

  By focusing on the maintenance of machine tools and special machine, these companies help extend the life of their customers' products so they can be used for longer periods of time. This specialization in maintenance services helps conserve resources and reduce waste by maximizing the life of existing equipment. It also promotes a more sustainable approach to industry by supporting the circular economy and reducing the need for frequent replacement or disposal of machinery.

- **Sharing models:**

  The introduction of sharing models for machine tools and special machines or their components allows them to be shared by multiple customers. By offering machines or specific components for sharing, companies can optimize machine utilization and maximize resource efficiency. This approach promotes a collaborative and circular mindset, reduces the need for individual ownership, and enables more sustainable resource allocation in the industry.

- **Technical remanufacturing services:**

  Shifting the focus to remanufacturing and possibly upgrading existing machine tools and special machines offers a sustainable alternative to manufacturing new products. By using remanufacturing techniques, companies can restore machines to like-new condition, reducing the need for new production and minimizing waste, helping to conserve resources, create a circular economy and reduce the environmental impact of production processes.

- **Rental or leasing models:**

  By renting or leasing machine tools and special machines, companies can offer their customers a flexible and cost-effective solution. Renting or leasing allows customers to use the machines for a period of time without the burden of ownership, while companies retain responsibility for maintenance and repair. This approach promotes resource efficiency because the same machines can be used by multiple users over their service life, reducing the overall need for new machines.

These business models, which focus on extending product life, help reduce resource consumption and the need for new equipment. By offering repair options and service models, companies not only build long-term customer relationships, but also create value by extending product life. The practice of reusing products or components further increases resource efficiency and minimizes environmental impact, in line with sustainability principles and circular economy concepts.

3.1.3 Business models with growing customer requirements or more efficient technologies

If it is expected that customers will have additional requirements (e.g., additional testing of manufactured products), or if technological developments can lead to efficiency improvements (e.g., through faster inspections), business model strategies and related measures should be considered in terms of upgradability. This can be discussed in the context of different service models. Provided that additional customer requirements can be expected or that technological developments can lead to efficiency improvements, the following business models could be considered in the machine tool and special machine industry:

- **Upgrade services:**

  By offering modernization and upgrade services for existing machine tools and special machines, companies enable their customers to adapt to changing requirements and take advantage of technological advances without having to purchase new machines. These services can include replacing or integrating new components, upgrading control technology, or implementing new features to improve machine performance. This approach promotes sustainability by extending the life of machines, reducing waste and optimizing the use of resources.

- **Remote maintenance and support services:**

  The use of remote maintenance and support technologies enables companies to support their customers quickly and efficiently. By remotely monitoring machine tools and specialized machinery, technicians can diagnose problems, perform necessary software updates and make configuration changes without having to be on-site. This efficient approach saves time, reduces travel costs, and ensures that machines are always up to date, maximizing performance and minimizing downtime for customers.

- **Software-as-a-service (SaaS) [30]:**

  By offering machine control software as a service, companies allow their customers to subscribe to the software and receive regular updates and new features. This subscription-based model allows customers to keep their machine tools and special machines up to date with the latest technology without the up-front investment of purchasing a full software license. This approach promotes cost efficiency and flexibility, and ensures that customers have access to the latest software features throughout the lifecycle of their machines.

- **Training services:**

  In response to additional requirements and technological developments, companies can offer comprehensive training programs to help their customers use and operate their machines efficiently. These training programs can cover a range of topics, including the use of new technologies, additional testing procedures, and quality assurance protocols. By offering this training, companies can enable their customers to optimize the performance of their machines, ensure compliance with new standards, and improve overall operational efficiency.

These business models are designed to meet additional customer needs and leverage technological developments to add value. Upgrade services and the ability to customize machine tools and special machines allow customers to maximize their investment and stay at the forefront of technology. Remote maintenance, Software as a Service (SaaS) [30] and training enable companies to provide customers with ongoing support and the skills they need to meet new demands. By combining products and services, companies can build long-term customer relationships and strengthen their competitive position.

Estimating the effort required to implement these business model strategies is difficult due to differences in corporate structures, human resource requirements, supplier and customer relationships, and other factors that contribute to different corporate cultures. The classification presented is based on an initial assessment by the authors and recognizes the complexity of issues specific to the for the design of machine tools and special machines. It is important that each company conduct a thorough assessment of its specific situation to determine the feasibility and challenges of implementing these strategies.

3.2 Target-oriented design of products taking into account the specific business model strategy

It should be recognized that this classification is not exhaustive and that feasibility may depend on factors such as company size, industry, availability of resources and other individual considerations. In addition, measures are often interrelated or interdependent, requiring a holistic approach that takes into account technical, regulatory and other constraints, as well as business models. Successful adaptation and implementation requires a thorough understanding of company-specific circumstances and challenges, as well as careful selection and adaptation of individual business models. The following are key measures for integrating sustainability into product design:

- **Life cycle management and assessment:**

  A holistic view of the product life cycle is crucial for cost optimization and sustainability. Product design should take into account factors such as durability, retrofittability, maintainability and spare parts availability to minimize unplanned downtime and costly repairs. By conducting LCA, companies can evaluate the environmental impact of their products throughout their life cycle and identify and address problem areas. By integrating these considerations into product design, companies can achieve greater sustainability and cost efficiency.

- **Implementation of eco-design principles:**

  The application of eco-design principles is crucial to the development of environmentally friendly products. By incorporating environmental considerations into the design process, companies can make sustainable choices, such as selecting materials with low environmental impact, reducing energy consumption and emissions, optimizing product life, and promoting recyclability. These eco-design principles contribute to the overall sustainability of the product and help minimize its environmental footprint throughout its lifecycle.

- **Promoting circular economy:**

  Promoting the circular economy is critical to sustainable product development. Companies can facilitate the reuse of materials and minimize waste by designing modular machines that can be easily disassembled and repaired. Incorporating recycled materials into product design and implementing take-back systems for used machines or components further support the principles of the circular economy by reducing resource consumption and promoting the efficient use of materials throughout the product lifecycle. These measures contribute to a more sustainable and resource-efficient approach in the machine tool and special machine industries.

- **Development of resource-efficient products:**

  Resource-efficient product design is the key to sustainability. Companies can prioritize the resource-efficient design of machine tools and special machines and their components by incorporating recycling-oriented design principles. This can include using high-quality, durable components and spare parts, considering reuse and recycling options in the design phase, and optimizing material use to minimize waste. By focusing on resource efficiency, companies can help conserve resources and reduce environmental impact throughout the life cycle of their products.

- **Optimization of material selection:**

  Optimizing material selection is an important aspect of sustainable product development. Companies can prioritize the use of sustainable materials, such as recycled or bio-based materials, which have a lower environmental impact than conventional materials. Selecting materials with a low carbon footprint and minimal resource consumption will help reduce the overall environmental impact of the product, promote resource efficiency, and support a more sustainable approach in the machine tool and specialty machinery industry.

- **Facilitation maintenance and repair:**

  Facilitating maintenance and repair is critical to promoting sustainability. Machines should be designed with easy access to key components, standardized parts and interfaces, and clear maintenance and repair instructions. Simple maintenance procedures increase efficiency and minimize downtime, while high-quality, robust construction extends machine life. In addition, modular design allows individual components or modules to be replaced and upgraded without having to replace the entire machine. This approach minimizes waste, conserves resources and promotes sustainability in the machine tool and special machine industries.

- **Reduction of resource consumption through remanufacturing and reuse:**

  By choosing to remanufacture, companies can minimize the amount of material and energy needed to manufacture new machines and use resources more efficiently. Repairing or replacing defective or worn parts, rather than disposing of the entire machine, reduces waste and supports the principles of the circular economy, which reuses resources and minimizes waste. This approach contributes to resource

conservation and the overall sustainability of the machine tool and special machine industries.

- **Improving energy efficiency:**

  Energy efficiency is an important factor in reducing operating costs and environmental impact. Companies can implement energy-efficient technologies, monitor energy consumption, and identify opportunities for energy savings to minimize energy costs. When modernizing equipment, measures can be taken to improve energy efficiency, such as replacing outdated components with more energy-efficient alternatives or optimizing control and drive systems. Reducing energy consumption not only saves money, but also reduces the environmental footprint - a win-win situation for companies committed to sustainability.

- **Use of digital technologies:**

  The use of digital technologies such as the Internet of Things (IoT), artificial intelligence (AI), and big data analytics offers significant benefits in optimizing energy consumption and monitoring product lifecycles. By using these technologies, companies can improve resource efficiency and promote sustainability. Information technologies enable better monitoring of machines and equipment through continuous collection and analysis of operational data. This enables proactive maintenance planning, identification of upcoming maintenance needs, and avoidance of unplanned downtime, resulting in improved operational efficiency and reduced energy waste.

- **Promoting of technological innovation:**

  Driving technological innovation plays a critical role in achieving sustainability goals, especially in saving energy and resources. Companies can drive sustainable product innovation by using energy-efficient machinery, implementing Industry 4.0 concepts to optimize production processes, and adopting low-emission technologies. By integrating these innovative approaches into their corporate culture, companies can lead the development of environmentally friendly and resource-efficient technologies and solutions and contribute to a more sustainable future.

- **Training and awareness-raising measures:**

  Education and awareness are critical to fostering a sustainable mindset in organizations. By training employees in sustainability and environmental protection, companies can raise awareness of these issues and emphasize their importance. This can inspire employees to come up with innovative ideas and solutions, and encourage the integration of sustainability principles into work processes and product development. Empowering employees through training and awareness helps create a culture of sustainability that promotes continuous improvement and a collective commitment to sustainable practices.

- **Cooperation with suppliers and partners:**

  Working closely with suppliers and partners is critical to promoting sustainable practices throughout the supply chain. Companies can work with suppliers that adopt green manufacturing practices, collaborate on sustainable solutions, and implement transparency measures. Establishing criteria for selecting suppliers based on their sustainability performance, such as environmental compliance and social responsibility, ensures alignment with sustainable goals. Through co-development activities, knowledge sharing, and collaborative research, companies and their partners can drive innovation and develop products that are more environmentally friendly, energy efficient, and socially responsible. Implementing supply chain transparency measures, such as traceability systems, audits and regular reporting, also helps identify sustainability risks and opportunities for improvement.

- **Promoting cooperation with customers:**

  Fostering collaboration with customers is critical to developing sustainable solutions. By involving customers in the development process, companies can gain insight into their specific needs and incorporate them into product development. The result is products that better meet customers' expectations and address their sustainability concerns. Customer engagement helps companies keep pace with changing needs, technological advances and emerging trends, so they can focus product development efforts on future needs and create innovative sustainable solutions. Customer engagement fosters loyalty and satisfaction, as satisfied customers are more likely to maintain long-term relationships and continue to purchase sustainable products. In addition, customers can provide valuable ideas, feedback and suggestions that contribute to the development of new sustainable products and solutions.

  Certifications and standards:

  Certifications and standards play an important role in promoting sustainability in the machine tool and special machine industries. Complying with sustainability standards and obtaining certifications such as ISO 14001 and ISO 50001 can help companies improve their sustainability performance and gain the trust of their customers. Although ISO 9001 is not a specific sustainability standard, it indirectly contributes to sustainability by promoting continuous improvement and meeting customer requirements. Eco-design approaches and methodologies enable the development of environmentally friendly products from the outset. Companies can also use voluntary reporting standards such as the Global Reporting Initiative (GRI) to communicate their sustainability efforts and report on environmental, social and governance issues. In addition, industry-specific tooling and specialty machinery initiatives provide valuable guidance for sustainable practices and innovation.

This comprehensive set of measures provides a wide range of options for advancing sustainability in the machine tool and special machine industry. Companies have the flexibility to choose a combination of these measures according to their specific circumstances and industry requirements to effectively pursue their sustainability goals. These measures are categorized into the three main variants discussed in sections 3.1.1 to 3.1.3 and visualized in Figure 3. This categorization helps companies identify the actions that are most relevant to their particular situation and facilitates a focused and strategic approach to sustainability integration.

By implementing these measures, companies can drive positive change, promote sustainable practices, and contribute to a greener and more resource-efficient industry.

3.2.1 Measures in response to significant changes in the framework conditions (variant 1)

To close the loop quickly and efficiently, products must be designed to be recyclable. This means that products must be designed to be easily disassembled, taking into account the potential effects of aging and wear. Extensive research has been conducted to identify disassembly-friendly design principles, emphasizing the importance of effective separation techniques and the selection of appropriate materials [31]. The ultimate goal is to enable disassembly at the individual material level, emphasizing the importance of disassembly-friendly material pairings at the design stage. Companies that emphasize recyclable design from the outset can facilitate efficient recycling processes and minimize waste. This includes factors such as labeling and segregating recyclable components, eliminating adhesives or other joining techniques that make disassembly difficult, and using standardized closures that facilitate disassembly. In addition, clear disassembly instructions and guidelines can be provided to facilitate proper recycling. By proactively planning for recycling during the product development phase, companies can contribute to a more sustainable, circular economy.

In addition to disassembly, the focus should be on developing material combinations and compounds that can be effectively separated in recycling processes. This requires careful testing of material compatibility and the use of appropriate joining techniques to enable efficient disassembly and separation of components. The introduction of standardized closures or labeling systems can facilitate the identification and separation of different materials and streamline the recycling process.

The integration of recyclable and environmentally friendly materials should also be a priority in product development. Selecting materials with a lower environmental impact, such as recycled or bio-based materials, can contribute to the overall sustainability of the product and reduce its environmental footprint.

Collaboration with recycling and waste management stakeholders is critical to the successful implementation of recyclable design. By working with recycling experts, companies can gain valuable insight into current recycling practices, new technologies and material recovery processes. This collaboration facilitates the identification of opportunities for improvement and innovation in product design and ensures that end-of-life considerations are incorporated into the development process from the outset.

When incorporating recycled and recovered materials into product design, it is also important to consider the specific properties and characteristics of these materials. A thorough evaluation of their performance, durability and compatibility will ensure that they meet the required standards and can be seamlessly integrated into the design process.

Overall, by working with recycling and waste management stakeholders and incorporating recycling-friendly design principles, companies can contribute to a circular economy and promote a more sustainable approach to resource management. By actively engaging in these practices, companies can optimize material recovery, minimize environmental impact, and drive positive change throughout the product lifecycle. Companies can actively contribute to the circular economy by incorporating recycling-oriented design principles into product development. This includes designing products for easy disassembly, using material separation

techniques, and using recyclable materials. By adopting these practices, companies support the efficient and sustainable use of resources and the recovery of valuable materials. This in turn reduces dependence on virgin raw materials and minimizes waste generation.

3.2.2 Measures in response to no significant change in framework conditions (variant 2)

In variant 2, service-friendly product design (service refers to maintenance and repair) is crucial. This includes implementing measures that directly support maintenance and repair activities, such as ensuring easy access to relevant components. In addition, it may be necessary to provide monitoring capabilities to effectively monitor product health, which can be achieved through the use of digital twins [32, 33].

A modular product design improves maintenance and repair processes because the product can be divided into smaller, replaceable modules. This allows easy access and replacement of specific components without extensive disassembly or the use of special tools. In addition, incorporating self-diagnostic capabilities into the product design can help identify potential problems or malfunctions. This can be achieved through built-in sensors that monitor performance parameters and provide real-time feedback to maintenance teams, facilitating proactive maintenance and timely repairs.

Standardized maintenance procedures are essential to ensure consistency and efficiency in maintenance and repair. Clear guidelines and protocols should be developed and communicated to maintenance personnel to streamline their tasks and minimize the risk of errors or unnecessary downtime. Products should be designed to facilitate troubleshooting through clear displays, fault codes or diagnostic interfaces that allow maintenance personnel to quickly identify and correct problems. Easy-to-use interfaces and intuitive error messages can contribute to efficient troubleshooting and reduce the time required to diagnose and resolve problems.

In addition, the design should consider the product's operating environment and provide safeguards to reduce potential damage from external factors such as dust, moisture or temperature fluctuations. This can help extend the life of the product and reduce the frequency of maintenance interventions. Involving maintenance teams early in the product development process can provide valuable insight and feedback. Their expertise can help identify potential maintenance challenges and opportunities for improvement, and ensure that maintenance requirements are properly considered in product design.

This underscores the importance of considering various aspects of a maintenance-friendly design, such as modularity, self-diagnostic capabilities, standardized procedures, troubleshooting support, environmental considerations, and collaboration with maintenance teams. By incorporating these elements into product design, manufacturers can improve the serviceability and longevity of their products, leading to greater sustainability and customer satisfaction.

3.2.3 Measures in response to growing customer requirements or the availability of more efficient technologies (variant 3)

In addition to the measures described in Variant 2, new components with different or changed properties are integrated during the product upgrade process in Variant 3. Therefore, it is critical to analyze the impact of these changed (emergent) component properties on the overall product.

This analysis can be based on approaches derived from robust design principles [33–35]. When integrating new components, their compatibility and integration into the existing product structure must be carefully evaluated. This includes evaluating potential interactions, dependencies, and performance impacts resulting from the introduction of these components. Extensive testing and simulation may be required to evaluate the behavior of the overall system and ensure that desired functionality and performance are maintained [36].

To address these challenges, the principles of robust design can be valuable. Robust design focuses on optimizing products and processes to withstand variability and uncertainty and ensure consistent performance even as components change.

In addition, a thorough understanding of the product's functional requirements and the specific goals of the upgrade is essential. Once the desired outcomes and performance goals are clearly defined, designers can make informed decisions about the selection and integration of new components. Considerations include energy efficiency, compatibility with existing systems, ease of integration, and the potential for future upgrades or customization.

Collaboration between the product development team, component suppliers, and other relevant stakeholders is critical during the upgrade process. This collaboration facilitates knowledge sharing, enables the identification of appropriate upgrade options, and helps ensure the seamless integration of new components into the existing product structure. Regular communication and feedback loops between all stakeholders are key to successful implementation.

By effectively managing the challenges associated with product upgrades and addressing the new features of new components, companies can extend the service life and functionality of their products. This approach promotes resource efficiency, reduces waste, and contributes to the company's overall sustainability goals.

	Measures in response to significant changes in the framework conditions (variant 1)	Measures in response to no significant change in framework conditions (variant 2)	Measures in response to growing customer requirements or the availability of more efficient technologies (variant 3)
Life cycle management and assessment			
Implementation of eco-design principles			
Promoting circular economy			
Development of resource-efficient products			
Optimization of material selection			
Facilitation maintenance and repair			
Reduction of resource consumption			
Improving energy efficiency			
Use of digital technologies			
Promoting of technological innovation			
Training and awareness-raising measures			
Cooperation with suppliers and partners			
Promoting cooperation with customers			
Certifications and standards			

Allocation

Figure 3. Allocation of the measures to the variants

4. CONCLUSION AND OUTLOOK

Sustainability in machine tool and special machine industry can be promoted through various strategies. These include principles of eco-design and resource efficiency, circular economy and life cycle management, energy efficiency and renewable energy, sustainable supply chain management, and the use of digital technologies. The paper discusses the importance of sustainability in the development of machine tools and special machines. It highlights the need for practical and validated means to make targeted decisions that take into account sustainability and circular economy aspects. In order to consistently integrate sustainability and circular economy principles, different strategies such as purchasing, leasing, deposit systems, pay-per-use and modification/upgrading are investigated. The impact of these strategies on various aspects, including business models and applicability, will be discussed. In addition, the importance of considering environmental costs, raw material costs, energy and auxiliary material costs, and maintenance costs in sustainable product development is highlighted. The systematized sustainability strategies presented and the resulting business models provide key insights for decision making.

In addition to familiar approaches such as purchasing, leasing and pay-per-use, innovative approaches include product-as-a-service, sharing models, circular supply chains and carbon compensation. These approaches help to minimize resource consumption, reduce waste, increase energy efficiency, and drive sustainability in tool and special machine industry. In the future, the development of methods and guidelines to support product development will be further pursued in order to make sustainability an immanent part in tool and special machine industry.

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